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PICATINNY ARSENAL TECHNICAL REPORT 3185

STUDY OF THE COMBUSTION OF A GRANULAR EXPLOSIVE BY OBSERVATION OF STRESS WAVES IN SURROUNDING LUCITE

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STUDY OF THE COMBUSTION OF A GRANULAR EXPLOSIVE BY OBSERVATION OF STRESS WAVES IN SURROUNDING LUCITE.

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ABSTRACT

High-speed framing camera photographs were used to observe the stress waves generated in thick-walled Lucite tubes (3 inches OD, 3/8 inch ID) and in a Lucite block termination, by shock and combustion processes within the axial core. The stress waves were observed using an argon bomb for backlighting and crossed polarizers. Results obtained for axial cores of air, inert powder, granular RDX, and C4 were used in interpreting the results for a core of 60/40 granular mixture of potassium perchlorate and aluminum. For the latter, it was concluded that although the elastic wave velocities in the Lucite exceed the combustion front velocity (900 m/s), there is no precursor action, via the Lucite, on the 60/40 mix. Intensification of luminosity in the core at the surface of the terminating block, prior to arrival of the front, was noted for air and 60/40 cores.

INTRODUCTION

The objectives of this study were as follows:

a. To observe the stress patterns generated by axial pressure pulses in both a thick-walled Lucite tube and in a solid terminating Lucite block located at the end of the tube. These patterns are generated by the initiating explosive charge placed at the other end of the tube, and by air shocks and detonations in the axial core (hole) of the tube.

b. To qualitatively explain the observed results.

c. To apply the knowledge obtained to decide whether there are any interactions between the combustion of a core of 60/40 potassium perchlorate/aluminum and stresses in the tube.

d. To use the stress patterns observed for a 60/40 core to deduce information about its combustion.

The last two objectives are concerned with the combustion of a granular mixture of potassium perchlorate (22 micron) and atomized aluminum (15 micron) in the weight ratio 60/40. For convenience, this mixture if often referred to as 60/40. The combustion of explosively initiated (by a 0.36-gram tetryl pellet) 60/40 confined in a thick-walled Lucite tube has been under study at this Arsenal (Ref 1, 2). Figure 1 shows the development of a stable propagation profile in a 3/8-in.-diameter axial column of mixture (loading density 1.5 g/cm^3) confined within a 3 in.-diameter, 20 in. -long Lucite tube. The photos shown are 96 microseconds apart and were taken with a Beckman-Whitley Model 189 Framing Camera using backlighting by an argon bomb for the early frames. The speed at which the combustion front progresses (about 900 m/sec) is lower than the elastic wave velocities in Lucite. Handbook values are for compression (dilatational) 2680; for shear, 1100). This raises the possibility that there is some precursor action in the Lucite affecting the combustion.

EXPERIMENTS

The experimental arrangement is shown in Figure 2. The Lucite tube is viewed by the framing camera between crossed polarizers (Polaroid Corp. Linear Polarizer HN 32, 0.030 inch thick) using argon bomb backlighting. Each experiment involved a combination of core mixture, initiation technique, termination block, tube length, and camera speed , all of which are summarized in Table 1 for those experiments selected for presentation. Figure 3 shows the various initiation techniques used to produce air shocks of different strengths. The arrangement shown in Figure 3 for 1646 was also used for initiating all other cores. The photographic record numbers (in the 1600's)

are used throughout the tables and figures to cross-index the results. Measurements of velocities, angles, etc., were made on each record and the associated velocities are summarized in Table 2. Each velocity was deduced from a plot of corresponding points on a framing camera record. The maximum error involved is 200 m/sec.

Enlargements of key frames of significant records were assembled in photographic montages and are presented as Figures 4 through 20. The montages show the frame numbers of the individual enlargements so that the time between these frames can be calculated from Table 1. Approximate dimensions follow from the fact that about 2 3/4 inches of the 3 inch-diameter tube is transparent and that a Lucite block dimension is given in Table 1.

The Lucite fragments, whenever they were of significant size, were collected and, where possible, the tube was reassembled to show the fracture pattern. These are shown in Figures 21 through 23. Notes appended to Tables 1 and 2 provide other details on the experimental design and results respectively.

RESULTS

The interpretation of each grouping of results is followed by an indented paragraph that presents the supporting evidence. Further interpretation is in the DISCUSSION section.

1. The following sequence of events occurs when the front in the core of the Lucite tube progresses at a supersonic rate with respect to the sonic velocity (2680 m/sec) in Lucite. Since the core front is supersonic re Lucite, it cannot be preceded by any front in the Lucite. The moving front in the core is accompanied by a pattern in the Lucite generated by the moving pressure pulse within the core. This can be constructed as the envelope of the wavelets from each point that has been passed. This construction leads to the conical patterns observed. The leading inclined front is the compression wave, the interior front is the shear wave. These two waves are weak shocks. As the core front velocity decreases, the generating pressure drops and the velocities in the Lucite approach those of weak elastic waves (dilatational and shear).

> The above described phenomenon can be observed by looking at the profiles in Figure 4 for velocities greater than 2680 m/sec, or at the individual records for cores of C4 (Figure 5), RDX (Figure 6), and supersonic (re Lucite) air shocks (Figures 7, 8, 9). Table 2 has the results arranged in the order of decreasing core front velocity, showing that the velocities associated with the inclined compression front decrease correspondingly from weak shocks to the sonic limit, 2680 m/sec, as the core front itself approaches this value.

2. The following sequence of events occurs when the front in the core within the Lucite progresses at a subsonic rate (re Lucite). The initiating explosive generates a shock in the Lucite tube as well as in the core. The former quickly decays to the sonic velocity of 2680 m/sec, and progresses within the Lucite in the form of a front perpendicular to the axis. Rarefactions and reinforcements occur behind this front and it is reflected at the end of the tube. A complex time-dependent strain pattern thus develops in the Lucite tube. The subsonic core front (unless attenuated by inert powder) proceeds down the core, generating wavelets continuously which go in all directions, further altering the strain pattern in the Lucite. The strength of these wavelets depends on the core pressure, its duration, and the impedance coupling to the Lucite. Although the subsonic rate precludes an accompanying

sharp pattern of the type noted for a supersonic core front, there can still be an accompanying higher pressure region because the wavelets can be stronger near the core front and decay as they proceed outward.

In Figure 4, the upper right photo (or Figure 8, lower right) shows the front that is observed to propagate when the core is an inert powder. In Figure 8, one notes that a similar front follows after the pattern of accompanying direct and reflected shocks of the supersonic (re Lucite) air core shock. In some cases, the ignition of the 60/40 granular mixture was delayed and one could then observe the front generated by the initiator. The left side of Figure 10 shows the initial progression of the front whereas the right side shows (for a different sample) how the pattern modifies with time. Figure 11 shows an air shock which is subsonic (re Lucite); see Table 2, and therefore progresses down the core without the typical pattern of a supersonic (re Lucite)air shock. In this case, no clear evidence of a local higher pressure near the front is observed.

3. The front velocity in a 60/40 mixture (about 900 m/sec) is subsonic with respect to both compression and shear elastic waves in Lucite (2680 and 1100 m/sec). It, therefore, produces no accompanying pattern of the supersonic type in the Lucite tube. It moves through the decaying stress pattern started by the initiator and may alter it slightly. The combustion zone profile does not appear to be altered by the variations of the stress intensities in the surrounding Lucite tube.

Figures 12 and 13 show the combustion zone of the 60/40 mixture progressing through the varying stress pattern in the Lucite tube. In Figure 12, frame 14, the profile is just entering the region of the Lucite tube between crossed polarizers. In Figure 13, the backlighting is increasing in intensity during the first three frames. Examination of the negatives of these and other records has shown no clear pattern of modification of the stress pattern that could be ascribed to the 60/40, but there is some indication (Figure 12, frames 16, 17; Figure 16) that there are local pressure effects in the vicinity of the 60/40 front. On the other hand, no modification of the 60/40 combustion zone profile that could be associated with the stress pattern was found.

4. A supersonic (re Lucite) core shock or detonation impacting on a terminating Lucite block generates a spherical shock wave.

> For C4 and RDX detonations, see Figures 5 and 6. For supersonic (re Lucite) shocks in air core, see Figure 7 and compare frame 19 of Figure 9 with Figure 14. Table 2 shows approximate velocities of the shocks in the terminating block.

5. A subsonic (re Lucite) core shock or detonation is moving within an already stressed Lucite confine. The shock on impact is not observed because of the lower impact pressures, the prestressed condition of the terminating block, and perhaps the longer times between frames. Following impact, an irregular opaque front, interpreted to be a fracture front, is seen to grow at a subsonic (re Lucite) rate. Opaque fracture fronts are sometimes observed to grow within the end section of the Lucite tube nearest the terminating block.

> Figures 15, 16, and 17 show the formation of the opaque fracture front in the terminating block when the 60/40 core front impacts. Figure 18 shows the formation of such a front in the Lucite tube after passage of the tip of the combustion zone. In Figure 9, there is an opaque front generated in both tube and block after reflection of a supersonic (re Lucite) shock in an air core. This figure was taken at the same framing rate as those used for impacts by 60/40 cores. The impact shock is observed in frame 19 of this figure (compare with Figure 14), showing that the fracture fronts occur on reflection of the shock.

6. For both shocks in air cores and the detonation of the 60/40 core, it was found that there was an intense light emitting region generated in advance of the front at the terminating surface, just before impact. Note that for 60/40, this region is parallel to the termination, not to the detonation front, which is inclined at a steep angle, and occurs at the instant of contact of the inclined tip, (see DISCUSSION)

> This phenomenon for an air shock impact can be seen in Figure 9, frame 17, and Figure 19, frame 18. The analogous effect for a 60/40 core can be seen in Figure 16, frame 17; Figure 17, frame 22; and in Figure 20, frame 9. For the last named, the termination was only a 0.005 in. brass shim.

7. The 60/40 combustion zone profile has been observed in three forms. One consists of a highly luminous tip only a few millimeters wide, followed by a drop in luminosity and then a region in which the luminosity builds up rapidly as the chemical reaction accelerates. In the second, the entire profile appears uniformly luminous and in the third, the leading centimeter is much fainter than the rest. The front of the entire profile can be inclined and need not be marked by a sharp discontinuity in luminosity. Variations between these forms can occur in the same Lucite tube at different front positions. Luminous products capable of entering fracture fronts must come from beyond about one centimeter behind the front, since the forward part in all three forms represents only shock compression (see DISCUSSION). The reflection of the tip shock from the termination leads to a rarefaction entering the Lucite close behind the shock. Since the reflected shock produces a material velocity away from the interface, luminous products do not enter the fracture, leaving it opaque.

The greater luminosity of the first few millimeters of the 60/40 profile may be seen in Figure 15, frame 5, and Figures 17, 18, and 20. One also sees here that the luminosity is restored about a centimeter behind the front. Note the variation in front inclination in the different 60/40 core figures. Figure 18 shows an intensification of the tip which may be attributed to the variation in the pressure support conditions behind, due to the lateral fracture. Figures 12 and 13 show the first centimeter of the profile having low luminosity whereas Figure 16 shows luminosity matching the region behind. In Figure 18 the lateral fracture front seems to grow from a point behind the tip. Luminous products enter only as the region of chemical reaction reaches the fracture. As the fracture catches up to the tip (frame 23), the tip loses luminosity. This is restored on impact. Compare the fracture fronts in the terminating blocks of Figures 15, 16, and 17 with Figure 18. Note their complete lack of luminosity, so that chemically reacting products have either not entered or have cooled on expansion. The latter is contradicted by Figure 18, so the material velocity argument is supported. In Figure 17, one can see that the fracture front occurs as the shock is reflected, generating a rarefaction.

8. The nature of the damage to the Lucite tubes by the initiating mechanisms used to produce air shocks depends on the strength of the explosive charge and its confinement. These control the peak pressure and duration of the shocks in both the Lucite tube and its core. A strong charge in contact with one end of the tube, but otherwise unconfined, produces a maze of fine fractures; whereas a weaker charge, confined by its placement in a brass tube within the core, provides a longer duration, weaker loading, which leads to large fragments. The supersonic (re Lucite) air shocks have an accompanying sharp stress pattern in the Lucite, which on reflection at a block termination, causes breakup of the Lucite tube in the vicinity. The same effect does not occur for air termination. In the subsonic air shock case, the Lucite tube does not fragment only at the termination end. Instead, the entire tube fractures into large fragments when rupture occurs. The shocks in the core cause fracture patterns near the impact point of the terminating block.

Use Figure 3 to note the initiating scheme and Figures 21 and 22 to observe the results. In 1645, 3.89 grams of unconfined PBX was used. This loading was presumably of short duration because of the lack of confinement. The damage to the Lucite tube at the initiator end was limited to crushing and many small fractures in the vicinity of the explosion. The undamaged section between is due to the short duration, and thus the rapid lateral decay of the shock in the Lucite. In 1647, only 0.36 gram of tetryl was used unconfined and it was separated from the end of the Lucite tube by a 0.060 in. polyethylene disk. The pulse to the Lucite from the explosive was both weak and short and thus the damage to the Lucite tube was negligible. In 1659 and 1646, the 0.36-gram tetryl pellet was placed successively deeper within the Lucite tube. The result is similar to 1645, with a shift in the center of the fracture pattern. In 1660 and 1661, only 0.28 grams of PETN was used, with the brass tube extending beyond it. (see Figure 3). This brass tube was recovered, slightly distended, but otherwise intact. Local crushing of the Lucite was almost eliminated, and the overall effect of the reduced, well confined explosive was to produce an air shock of 3200 m/sec (1900 when attenuated by inert powder), of longer duration.

A subsonic (r Lucite) air shock was present in 1659, 1661, and 1647, whereas a supersonic air shock was present in 1645 (5500 m/sec), 1646 (3800 m/sec), and 1660 (3200 m/sec). For the supersonic there was

fracture of the section of Lucite tube adjacent to the terminating block for 1645 and 1646. However, 1622, which was the same as 1646, except that there was no terminating block showed no end damage. The larger fragments produced in 1660 are believed to be due to the longer duration weaker shock rather than the reflection. For the subsonic (re Lucite) shocks the tubes were undamaged in the vicinity of the terminating block, except for 1661 which had the same fracture pattern as 1660 and for the same reason.

The damage to the Lucite terminating blocks by the air shocks consists of fractures radiating from the cores. The greatest effect is in 1645, involving the strongest shock. 1647 should be expected to have the least effect, but in fact, 1646 shows even less (almost no damage). This may be due to differences in how well the terminating block was cemented to the Lucite tube.

9. The explosive cores (C4, RDX, 60/40) completely fragmented the Lucite tubes, and, with the two exceptions shown in Figure 23, did the same to the terminating blocks.

The RDX granular explosive core (1649) caused an extensive fracture pattern in the block, with rupture at external surfaces and a pattern indicating release wave effects. The 60/40 sample (1653) had some unique condition which removed large fragments from the block near the Lucite tube but left the rest intact. The lack of crushing in the latter case as compared to the former shows the contrast between a sharp, strong pulse (RDX) and a long duration weaker one (60/40).

DISCUSSION

It has been noted that the air shock appears to be preceded by some precursor whose presence is only made evident when a terminating surface is interposed (Figure 9, frame 17 and Figure 19, frame 18). The true explanation of this phenomenon is not known. However, it may be related to either radiation or electrons in advance of the shock front. In this regard, W. G. Vulliet (Ref 3) has recently reported an effect in low density air due to the former and Ia. B. Zeldovich (Ref 4) has treated precursor effects for strong shocks. It is possible that the effects can not be observed for our combination of normal density air and moderately strong shocks until an obstacle is encountered.

For a 60/40 core front the source of the luminosity must be explained before considering the 60/40 precursor effect described under RESULTS (Figure 16, frame 17; Figure 17 frame 22; Figure 20, frame 9). The luminosity at the front might easily be ascribed to the interstitial air of the powder being compressed by the shock. However, J. H. Blackburn and L. B. Seely (Ref 5) have demonstrated that the light observed on passage of strong shocks through granular media stems from stagnation of the shock-accelerated powder rather than from compression of the interstitial gas. They quote S. Paterson (Ref 6) as indicating the same type of light exists in detonation of granular explosive pressings and they propose that the same stagnation mechanism is the source of the light. Since the 60/40 mixture is loose loaded rather than presses, the effect may be distributed over a greater length.

The variations in tip luminosity may be ascribed to the density fluctuations and the inherent random nature of light emission based on granular impacts in a mixture that has both a particle size distribution and thermal absorbing characteristics. It is interesting to speculate on what happens to the interstitial air. Presumably, some is entrapped and compressed and contributes to the luminosity when at the core surface. However, it is possible that the air is forced through the porous charge in advance of the compressed powder and represents an invisible precursor. E. Weger and E. F. Blick (Ref 7) have shown, using a simplified model of a porous medium, that for a pressure differential of about one kilobar a local exit pore velocity of about 300 m/sec can be expected. In our case, the front velocity is about 900 m/sec, but the pressure is estimated as near 5 kilobars (based on Hugoniot calculated from compression data and the observed propagation speed). It is therefore not impossible that there is a flow of air in advance of the density and pressure jump. This precursor could lead to the impact luminosity effect observed on reaching the termination block. The luminosity would be parallel to the

termination because the air stagnates at the block. Although this explanation of the precursor for 60/40 is only a hypothesis, it seems more reasonable than either radiation or electrons threading through the maze of interstices of the opaque granular medium. It is, of course, possible to simply assume that the shock front is not luminous and preceeds the luminous front. However, one must then prove this hypothesis and also explain the observed luminosity variations which poses a new problem.

The powder compressed by the shock remains at a higher density than the original mixture. Since it consists of a mixture of fuel and oxidant particles, local reaction can occur, and the energy released can be absorbed in such endothermic processes as aluminum vaporization. It is believed that this competition provides the variation in luminosity of about the first centimeter of the profile. The sound velocity in the compressed accelerated powder is high enough to permit the strong chemical reaction zone behind to support the shock. The physical kinetics and shock Hugoniot of the 60/40 mixture are the subject of another report in preparation. For this reason, only the above qualitative picture, required to understand the effects observed in the Lucite tube and termination, is presented.

The results presented and flash radiographs show that the rupture of the Lucite tube does not occur near the front, but rather in back of the strong chemical reaction zone. The pressure at the shock front is calculated at about 5 kilobars and the critical dynamic tensile stress for Lucite is about 1 kilobar (Ref8). The pressure transmitted from the core to the outer surface of the Lucite tube, where the rarefaction wave would start, would be expected to attenuate below 1 kilobar (Ref 9). Hence, rupture would not occur until the greater stresses of the chemical reaction zone were applied.

When the front in the 60/40 core impacts on the termination block, a shock of magnitude greater than 5 kilobars is generated in the block, and a shock is reflected back into the core. Numerical values can be calculated from the shock Hugoniots of the initial mixture, compressed mixture, and that of Lucite (Ref 10) by standard techniques (Ref 11). The shock reflected into the powder attenuates rapidly since the powder medium it enters is still capable of both absorbing some energy as non-directed kinetic energy and undergoing large frictional losses. The hydrodynamic attenuation is faster than usual because unloading waves in the compressed powder behind the shock travel faster than the shock, thereby hastening pressure equalization (see Refs 12 and 13 for concepts applicable to powders). Thus a release wave is quickly generated at the contact surface of the Lucite block, which is in compression behind the shock in it. The pressure drop will exceed 1 kilobar, generating the observed fracture fronts.

Impedance considerations can be used to supplement the experimental observation (reported in the RESULTS) that there is no significant precursor action through the Lucite influencing the combustion of the 60/40 mixture. Suppose there were a 10-kilobar shock in Lucite normally incident on an interface with uncompressed powder. The shock Hugoniot of the powder (pressure-particle velocity plot) is so much flatter than that for Lucite that one would generate a very small (less than 0.1 kilobar) shock in the powder and a rarefaction wave back into the Lucite. Stated differently, the Lucite shock displacement is too small to create significant compression in the loose powder. The same argument would hold for the incidence on the core of the complex pattern of pressure waves generated in the Lucite tube by the subsonic (re Lucite) combustion zone profile. If one adds to this the shock attenuation in the Lucite itself and that due to the geometry, it is not surprising that there is no precursor action. This conclusion differs from hypotheses advanced with respect to the role of thin-walled Lucite tubes in influencing the low velocity detonation of liquid explosives such as nitroglycerin (Ref 14, 15). However, the reason for this difference is believed to be that the liquid core has a good impedance match both to the initiating explosive and the Lucite walls, whereas, as pointed out previously, the powder has very poor coupling with these.

CONCLUSIONS

The stress patterns generated in the Lucite tube differ markedly as the core pressure front propagates at either a supersonic or subsonic rate (re Lucite). In the former case, the pressure pulse leads concentric conical compression and shear waves. In the latter case, stress wavelets run ahead of the front and coalesce to form an advancing sonic front perpendicular to the axis of the Lucite tube.

The 60/40 mixture propagates at a subsonic rate (re Lucite) and therefore moves through a time-dependent stress pattern in the Lucite tube. No influence on the combustion zone profile associated with the stress pattern was observed. No consistent alteration of the Lucite stress pattern adjacent to the moving combustion front in the 60/40 core was observed. It is concluded that there is no precursor action on the combustion of the 60/40 mix through the Lucite tube.

Shock and fracture patterns in the terminating Lucite block are related to impedance matching and release wave considerations. Fragmentation of the Lucite tube is governed by the pressure-time-position characteristics of the loading pulse and how the Lucite tube distributes and attenuates the load in relation to the critical tensile and shear stresses for rupture.

Core precursors which precede the luminous front and make their presence evident only on impact were observed for both air shocks and 60/40 combustions. Possible explanations were discussed, but no conclusions arrived at.

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TABLE 1 Design Of Experiments

Record Number	Tube Length	Core	Termination (See Note 1)	Initiation (See Note 2)	Time Between Frames Microsec. Betw. Fr.
1623	10 in.	Inert Powder	None	Tetryl	2.67
1622	10 in.	Air	None	Tetryl	2.67
1645	10 in.	Air	3½	PBX	2.0
1646	10 in.	Air	3 5/16	Tetryl	2.0
1647	10 in.	Air	3½	Tetryl (red)	4.0
1659	10 in.	Air	-	Tetryl (pdr)	8.0
1660	10 in.	Air	-	PETN	8.0
1661	10 in.	Air	3½	PETN (pdr)	8.0
1649	10 in.	RDX	3½	Tetryl	2.0
1662	10 in.	C4	3	Tetryl	1.33
1629	20 in.	60/40	None	Tetryl	16.0
1630	20 in.	60/40	None	Tetryl	16.0
1631	20 in.	60/40	None	Tetryl	16.0
1653	20 in.	60/40	3 13/32	Tetryl	8.0
1654	20 in.	60/40	-	Tetryl	8.0
1655	20 in.	60/40	-	Tetryl	8.0
1657	20 in.	60/40	.005 in. Brass	PBX	8.0
1658	20 in.	60/40	3.5	PBX	8.0

Note 1. Each dimension of the Lucite block termination was over 3 inches, except for 1647, 1659, and 1660, where the spacing between optically finished surfaces was only 1½ inches. For all blocks the dimension given above in inches is that parallel to the long axis of the tube. A dash indicates that the dimensions of the Lucite block used are not known.

Note 2. "Tetryl" indicates that a 0.36-gm, 0.325 in.-diam., 0.2 in.-long Tetryl pellet was cemented within the end of a brass tube, which was then inserted to a depth of 1 3/4 inches in the 3/8 in.-diameter in the Lucite tube. An electric detonator was then inserted in the brass tube to initiate the Tetryl (see 1646 in Figure 3).

TABLE 1 Notes (continued)

"Tetryl (red)" indicates the same brass tube was placed outside the Lucite tube, but in contact with a 0.060 in. thick polyethylene disk, which was cemented to the end of the tube. A weaker air shock resulted, due to the lack of confinement and the polyethylene (see 1647 in Figure 3).

"Tetryl (pdr)" indicates a short section of brass tube containing a Tetryl pellet followed by a ¼ inch of inert powder was placed just within the hole in the Lucite tube. An electric detonator was used to initiate the tetryl. A weaker air shock resulted due to powder attenuation and reduced confinement (see 1659 in Figure 3).

"PETN" indicates that an electric detonator whose explosive is PETN (280 milligrams) was used within the hole of the Lucite tube. PETN is weaker than Tetryl (see 1660 in Figure 3).

"PETN (pdr)" indicates that a ¼ inch of inert powder followed the detonator to weaken the shock (see 1661 in Figure 3).

"PBX" indicates that a 5/8 in. diameter, ½ in. thick (3.89 gram) pellet of PBX (stronger than Tetryl) was placed in contact with the end of the core of the Lucite tube. This was then initiated by an electric detonator (see 1645 in Figure 3).

TABLE 2 Velocities (m/sec) Observed In Experiments (Note 1)

Record Number	Core	Front In Core	Fronts In Lucite Tube (Note 2) Perpend. To Axis	Inclined Compression	Inclined Shear	In Lucite Block (Note 3) Stress	Fracture
1662	C4	6800	x	4800	-	-	-
1645	Air	5500	x	3300	1900	2600	-
1622	Air	4700	x	3600	2350	-	-
1649	RDX	4400	x	3500	-	3300	-
1646	Air	3800	x	-	1900	2500	-
1660	"(Note4)	3200	x	2900	-	-	830
1661	Air	1900	(Note 5)	x	x	-	-
1647	Air	-	(Note 5)	x	x	-	-
1659	Air	-	2600	x	x	-	-
1623	Inert Powder	x	2700	x	x	-	-
1629	60/40	950	2700	x	x	-	-
1630	60/40	-	(Note 5)	x	x	-	-
1631	60/40	910	(Note 5)	x	x	-	-
1653	60/40 (Note4)	900	-	x	x	-	500
1654	60/40	-	-	x	x	-	450
1655	60/40	750	(Note 5)	x	x	-	850
1657	60/40	930	(Note 5)	x	x	-	-
1658	60/40	930	(Note 5)	x	x	-	400

Note 1. The symbol x indicates that no such front is present. The symbol - indicates that the experiment gives no information on the item, as for example in 1623, where no Lucite block is present, or as in 1647, where the timing was too late to observe transient effects, or as in 1646, where the inclined compression was too indistinct for measurement.

TABLE 2 Notes (continued)

Note 2. A front, generated by the initating explosive, travelled down the Lucite tube. Since the front is perpendicular to the long axis, it is designated PERPEND. TO AXIS.

Two fronts were generated from the traveling high pressure region (shock or detonation) when supersonic relative to Lucite which by Huygens construction formed angles with the axis of the tube. The steeper (faster) front was designated INCLINED COMPRESSION and the other INCLINED SHEAR. Numerical values given were obtained by core front velocity multiplied by sine of their respective angles to the axis.

Note 3. A front traveling radially outward in either the Lucite block or the tube, from the impact point, as observed by change in polarization pattern, was designated STRESS, whereas an irregular pattern extending at a subsonic rate (re Lucite) and making Lucite opaque was designated a FRACTURE front. This latter velocity is approximate since the fracture front is not usually symmetric and may not progress perpendicular to the camera axis. (see photos for each record).

Note 4. The velocity of the front in the core for 1660 is based on an estimate of distance travelled in 64 microseconds, because a length calibration was not available for record 1660. The fracture velocity provided for 1660 and 1653 occurred at the end of the Lucite tube, not in the block.

Note 5. The timing for these records was such that the perpendicular to axis front generated by the tetryl pellet had already passed. Therefore, only the residual stress patterns due to this front were observed. For record 1661, and those for 60/40, the front in the core (air shock) is subsonic with respect to Lucite and thus, although it contributes to the overall stress pattern, it cannot have any inclined fronts in the Lucite tube. Note that for records 1659 and 1623, timing was sufficiently early to observe the passage of the perpendicular to axis front generated by the tetryl initiator, and for 1629 ignition of 60/40 was slow. For 1623, any initial core shock was quickly attenuated by the inert powder.

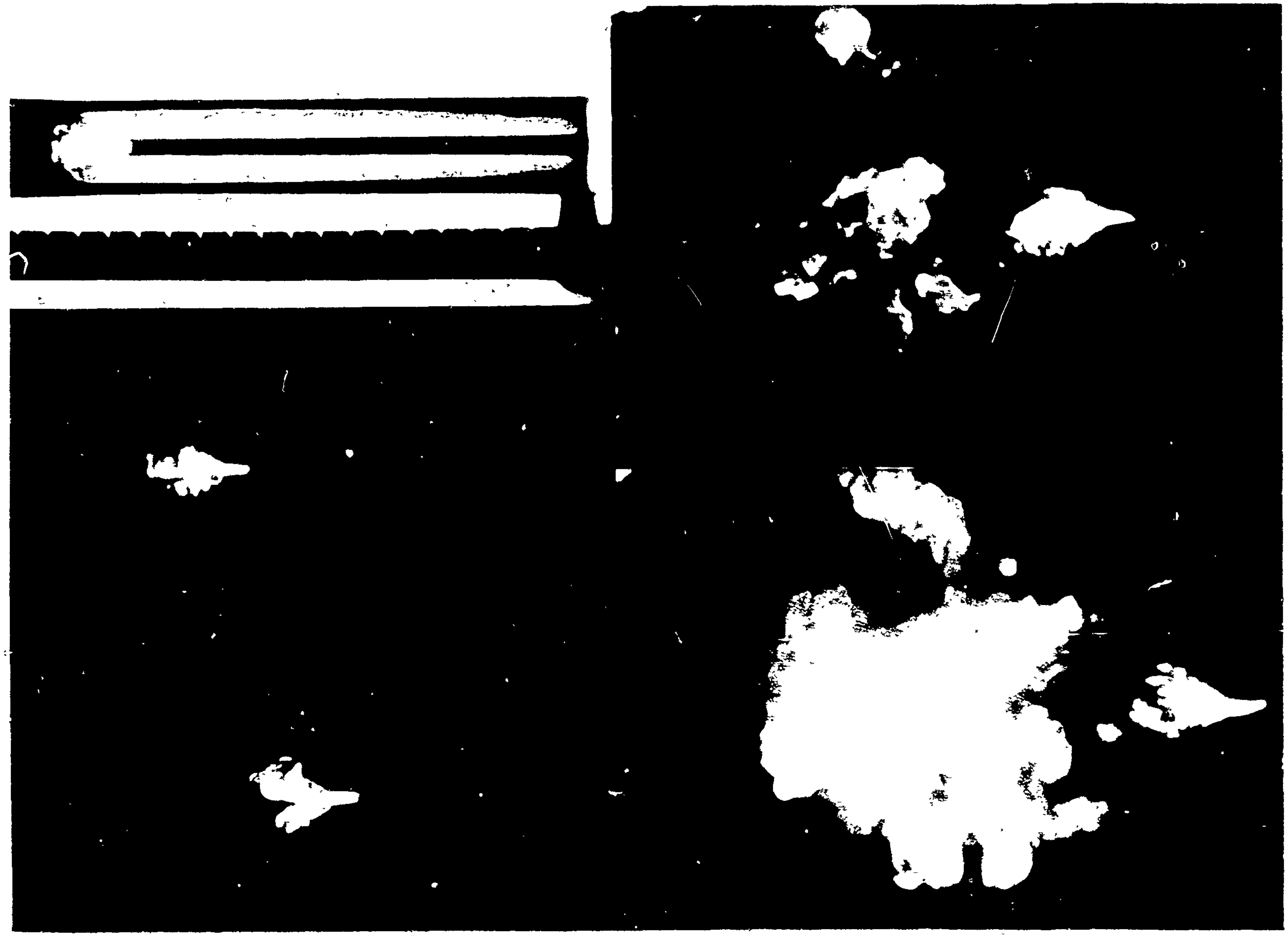

Fig 1 Propagation of combustion in a granular mixture of potassium perchlorate and aluminum (60/40) (Detonation velocity 900 m/sec, 96 microseconds between photos shown)

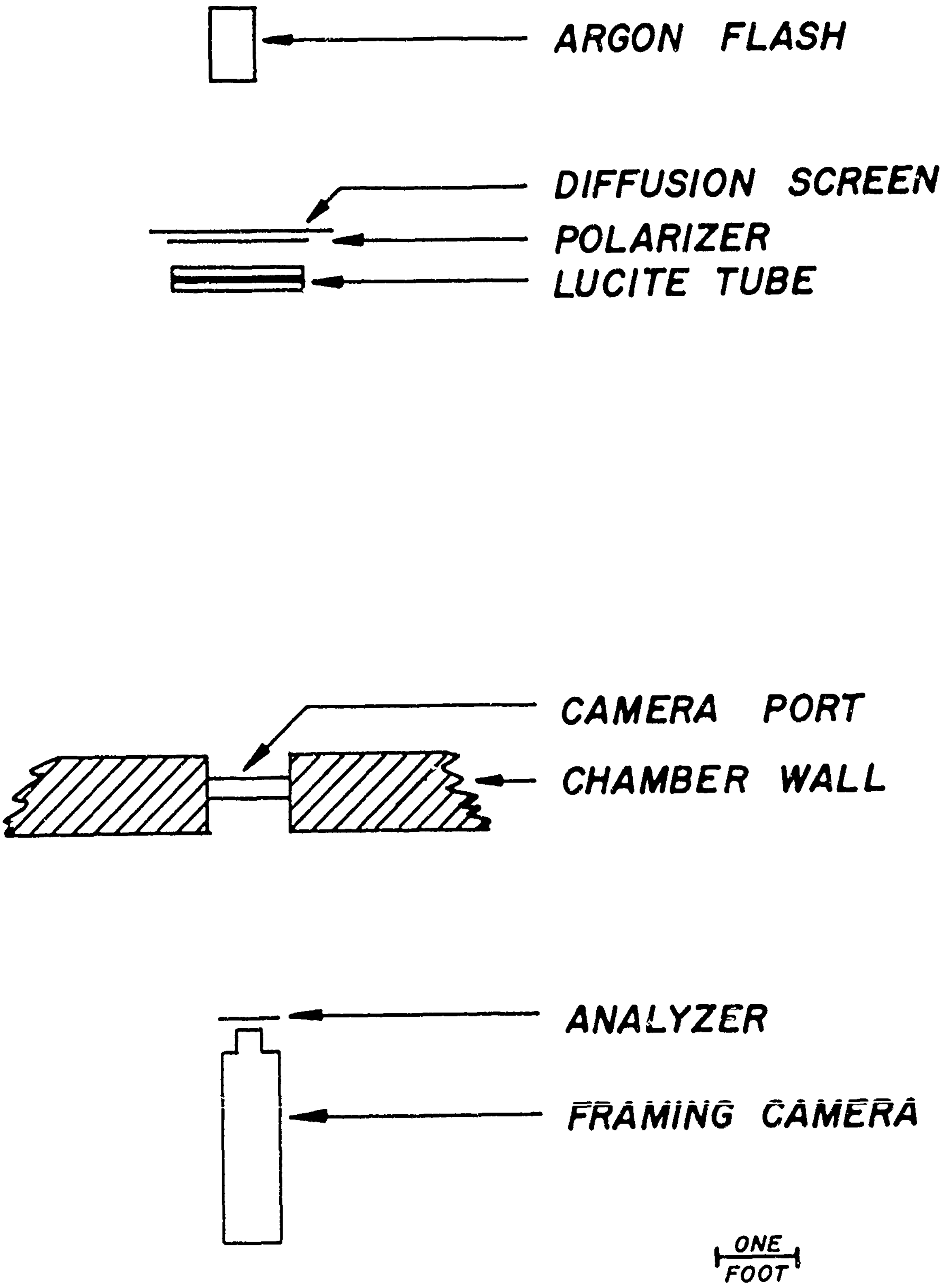

Fig 2 Experimental arrangement for observing stress patterns in Lucite

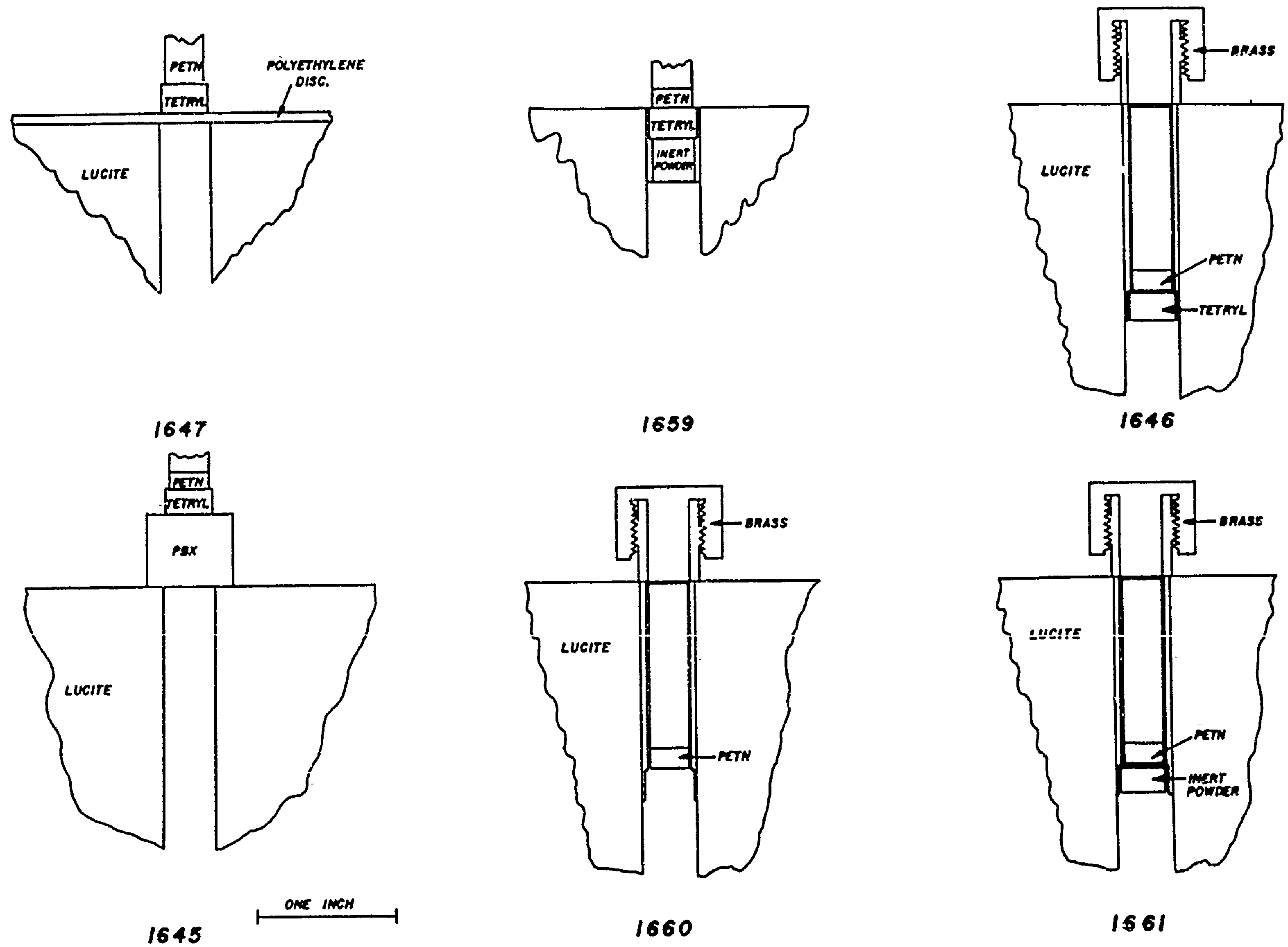

Fig 3 Initiation techniques used for producing air shocks of various strengths with all other core initiations same as 1646.

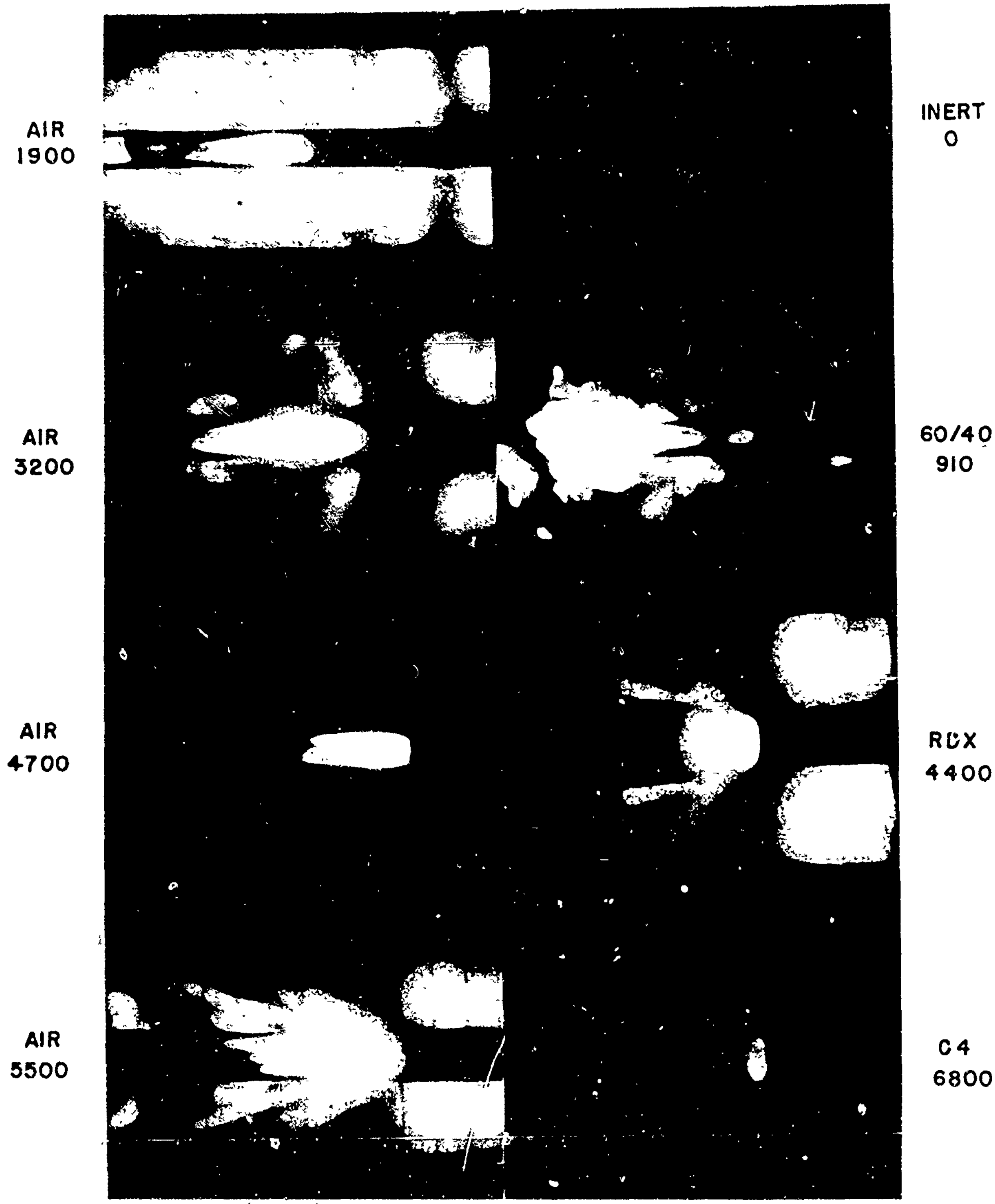

Fig 4 Profiles for various cores (Core front velocities in m/sec) In the upper right photo, the powder in the core absorbed the shock. The profile in the Lucite due to the initiator travels at about 2700 m/sec

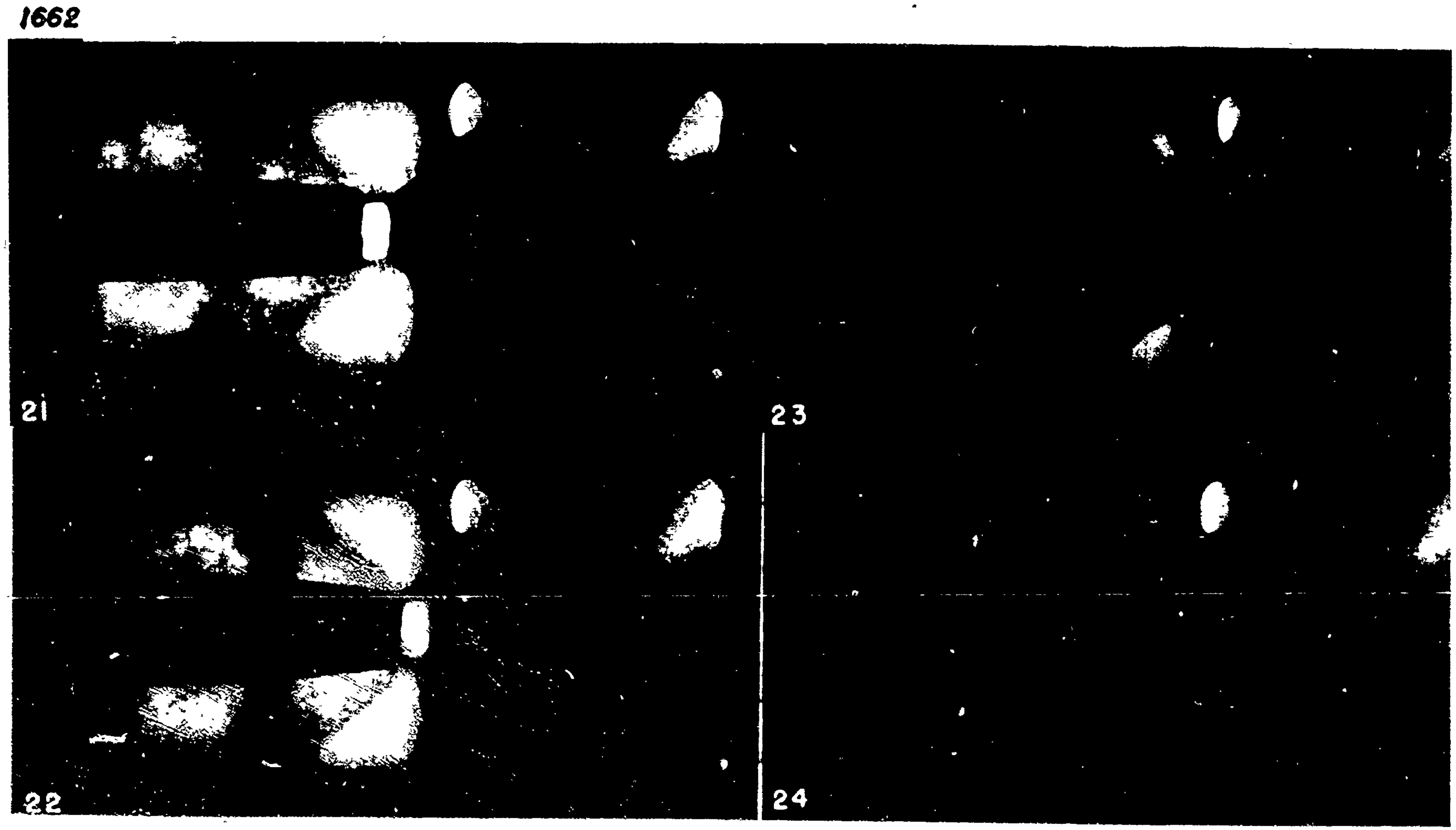

Fig 5 Impact on Lucite block of detonation front of
C4 explosive core (1662)

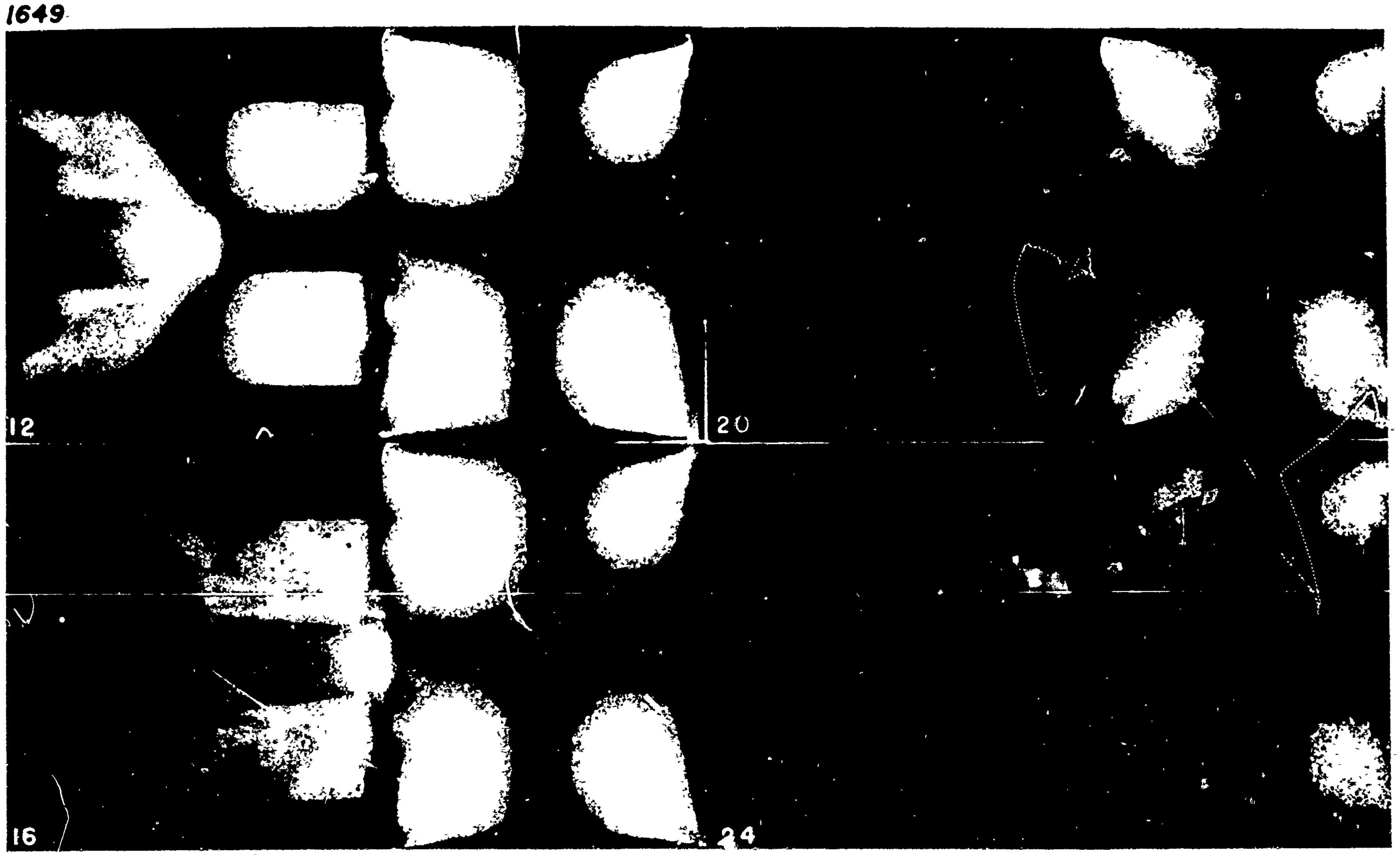

Fig 6 Impact on Lucite block of detonation front of RDX granular explosive core (1649)

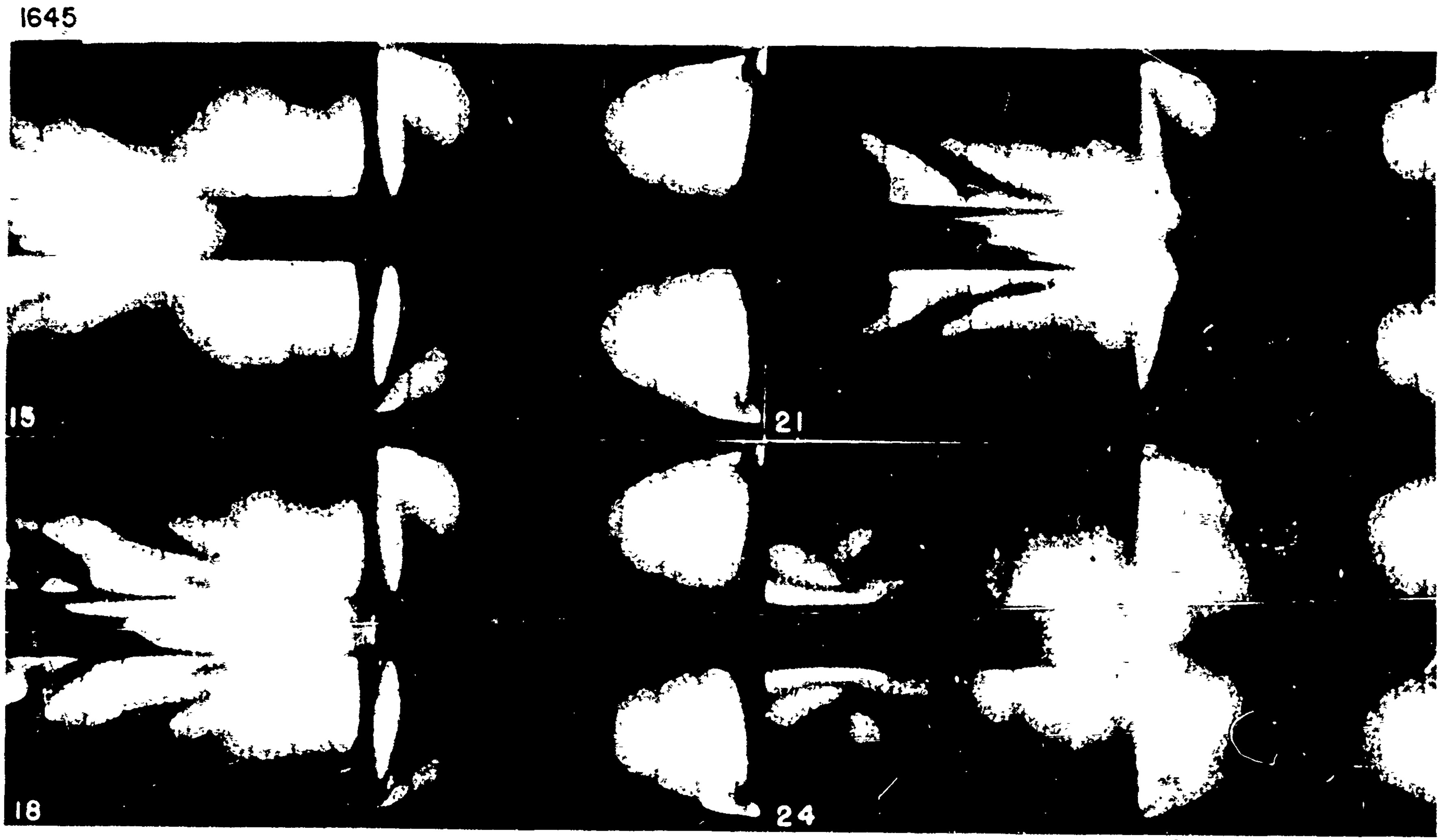

Fig 7 Impact on Lucite block of air core shock generated by PBX (1645)

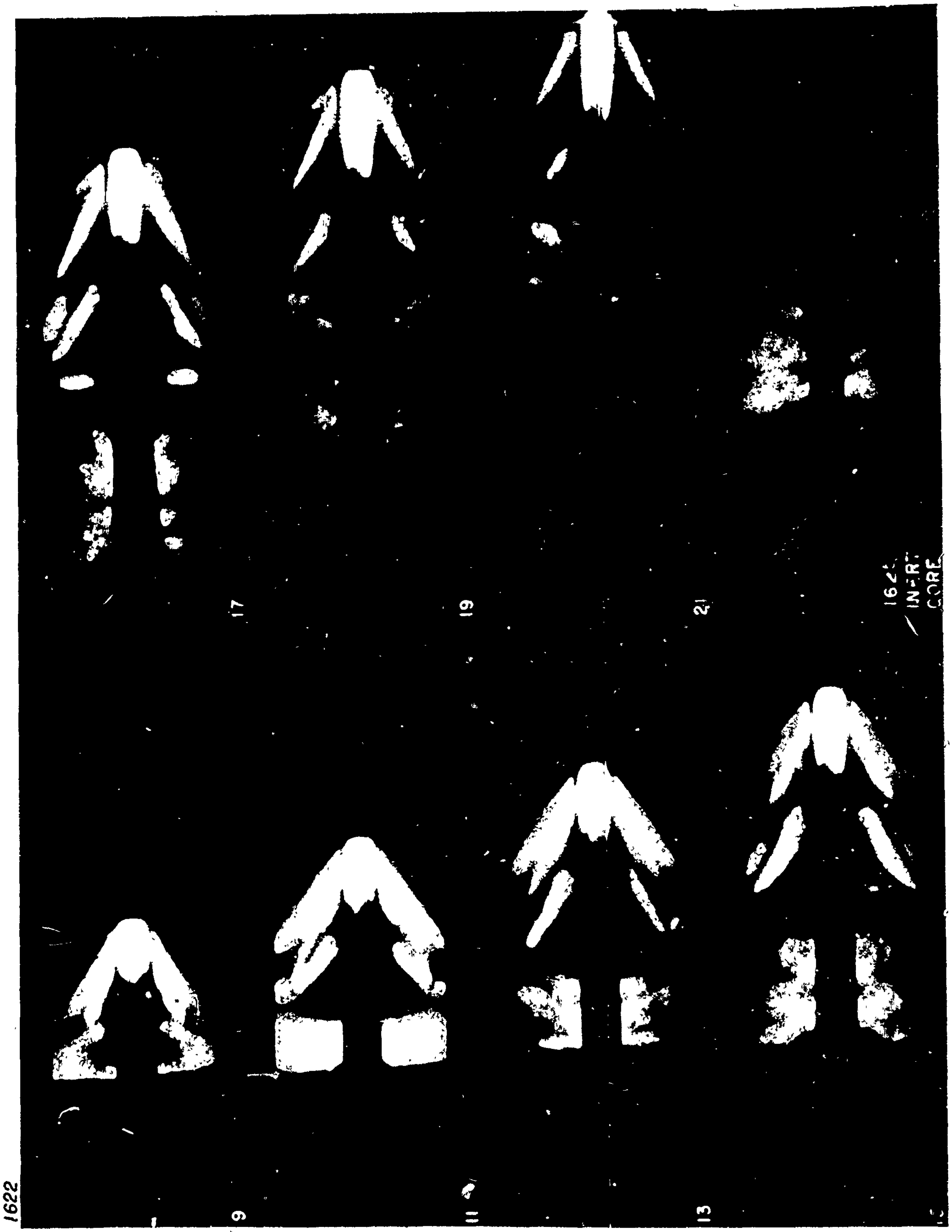

Fig 8 Profiles in Lucite tube for a shock in the air core generated by tetryl

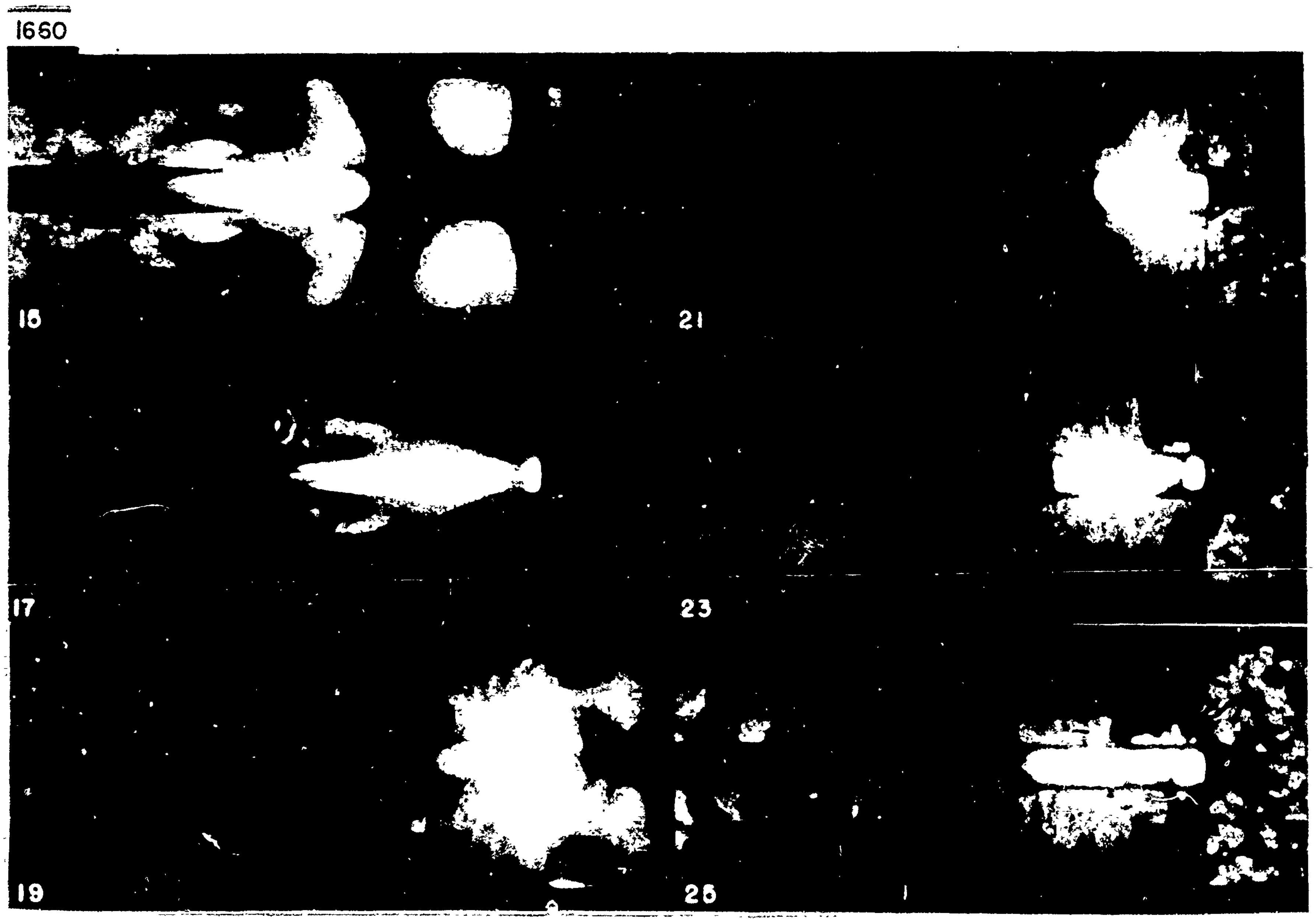

Fig 9 Impact on Lucite block of shock front in air core generated by PETN (1660)

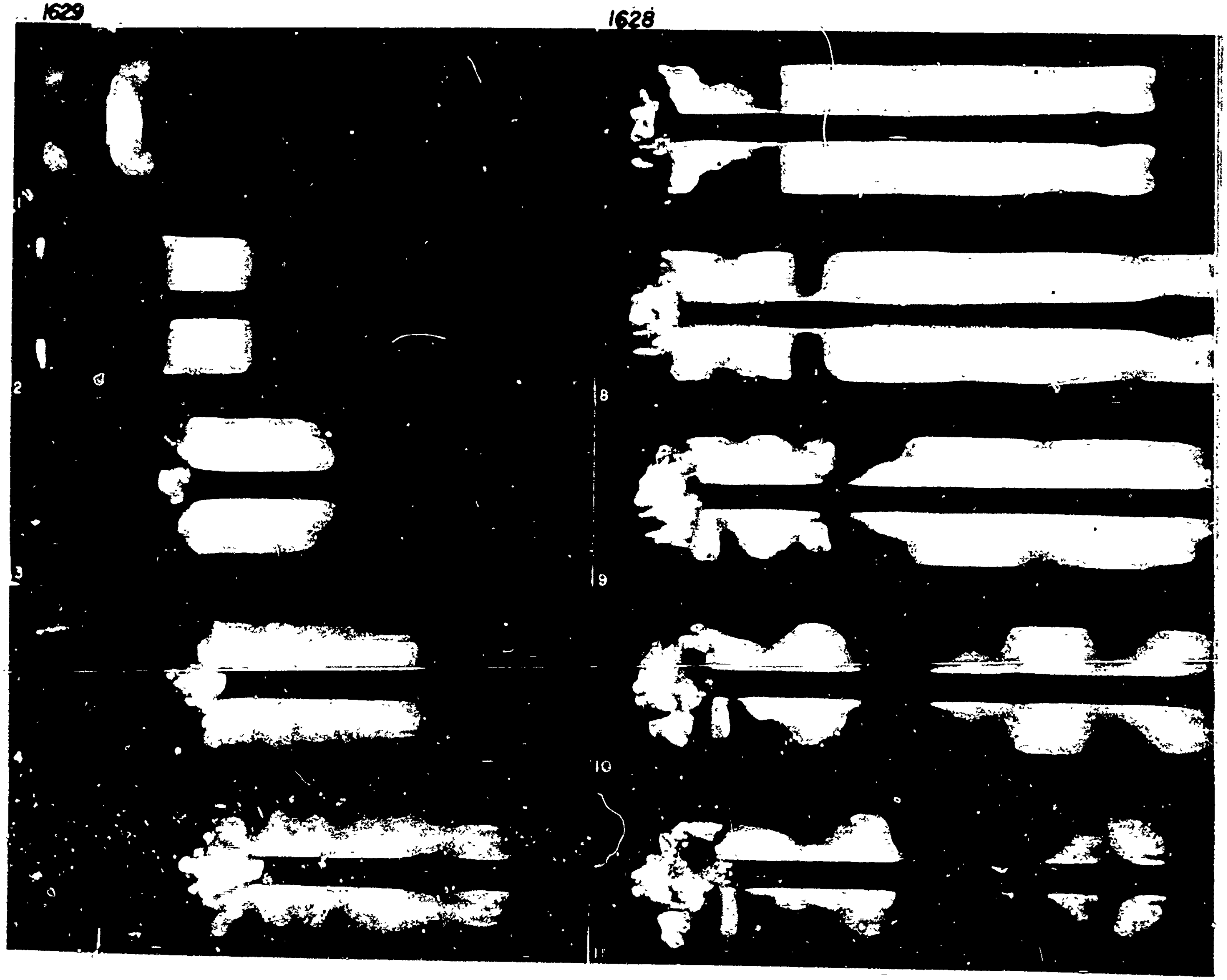

Fig 10 Stress wave in Lucite tube due to initiating pellet (1629) (1628)

1661

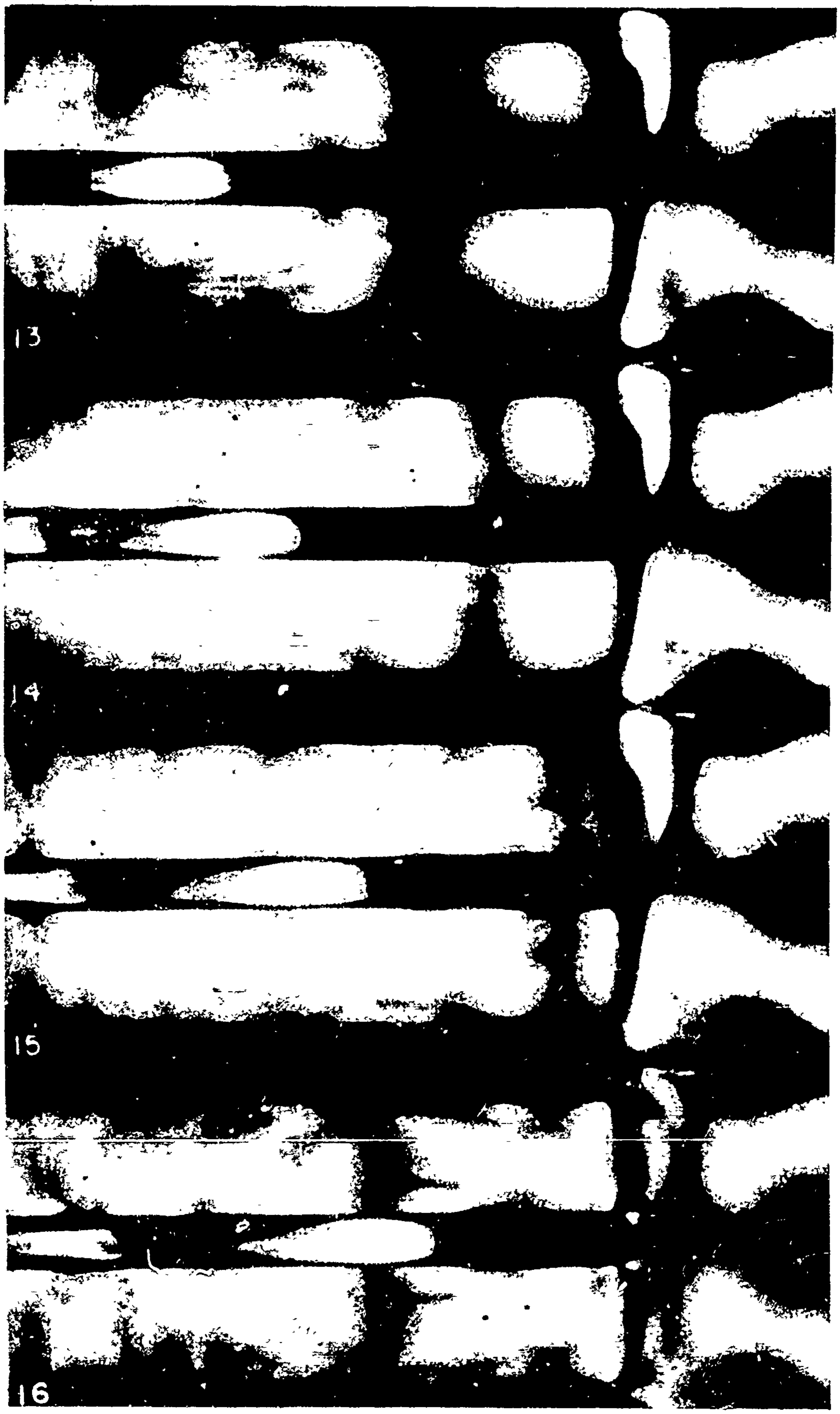

Fig 11 Stress pattern in Lucite tube air core shock (subsonic with respect to Lucite) (1661)

Fig 12 Combustion zone of 60/40 progressing through stress pattern in Lucite tube (1630)

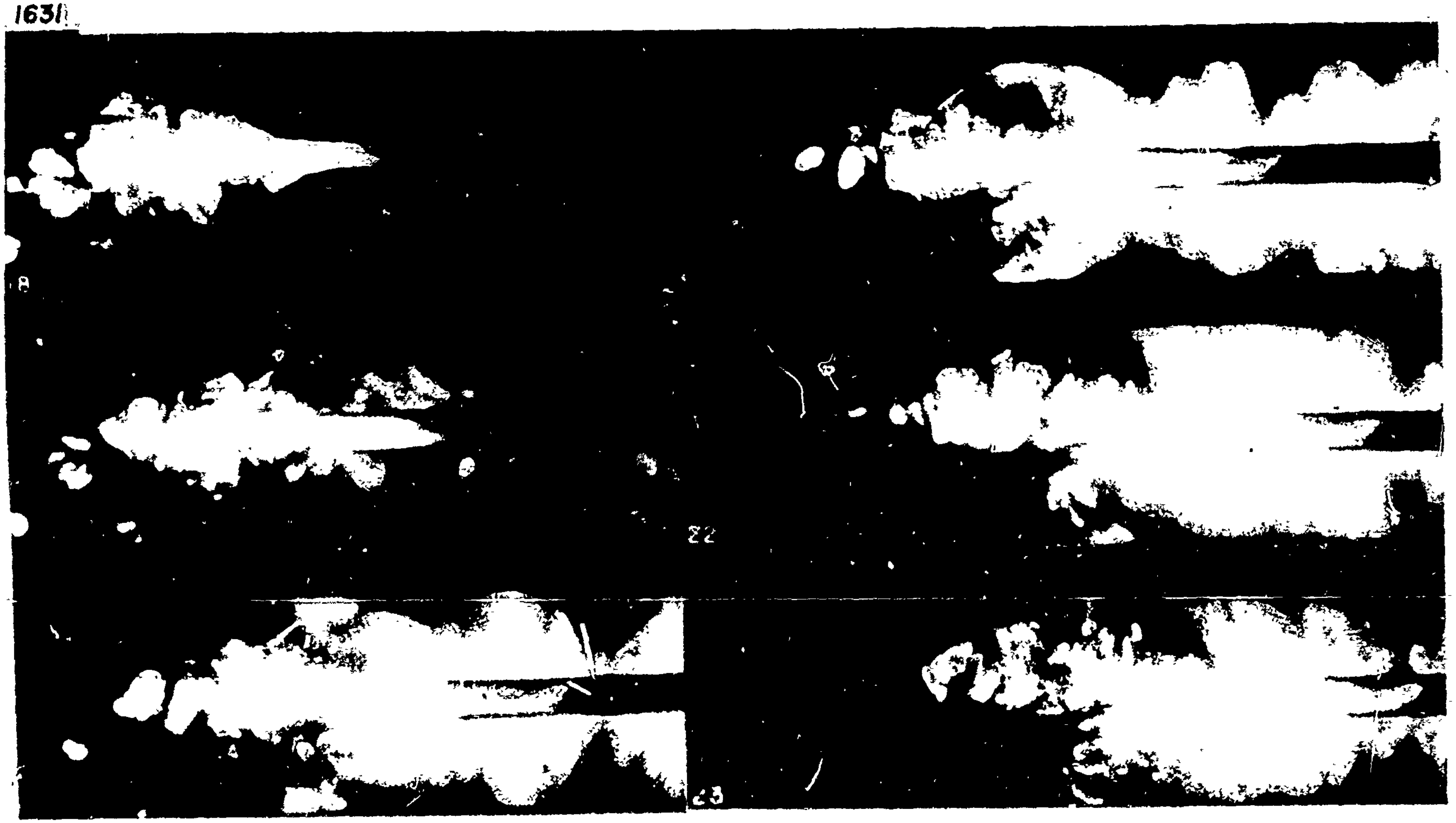

Fig 13 Combustion zone of 60/40 progressing through stress pattern in Lucite tube (1631)

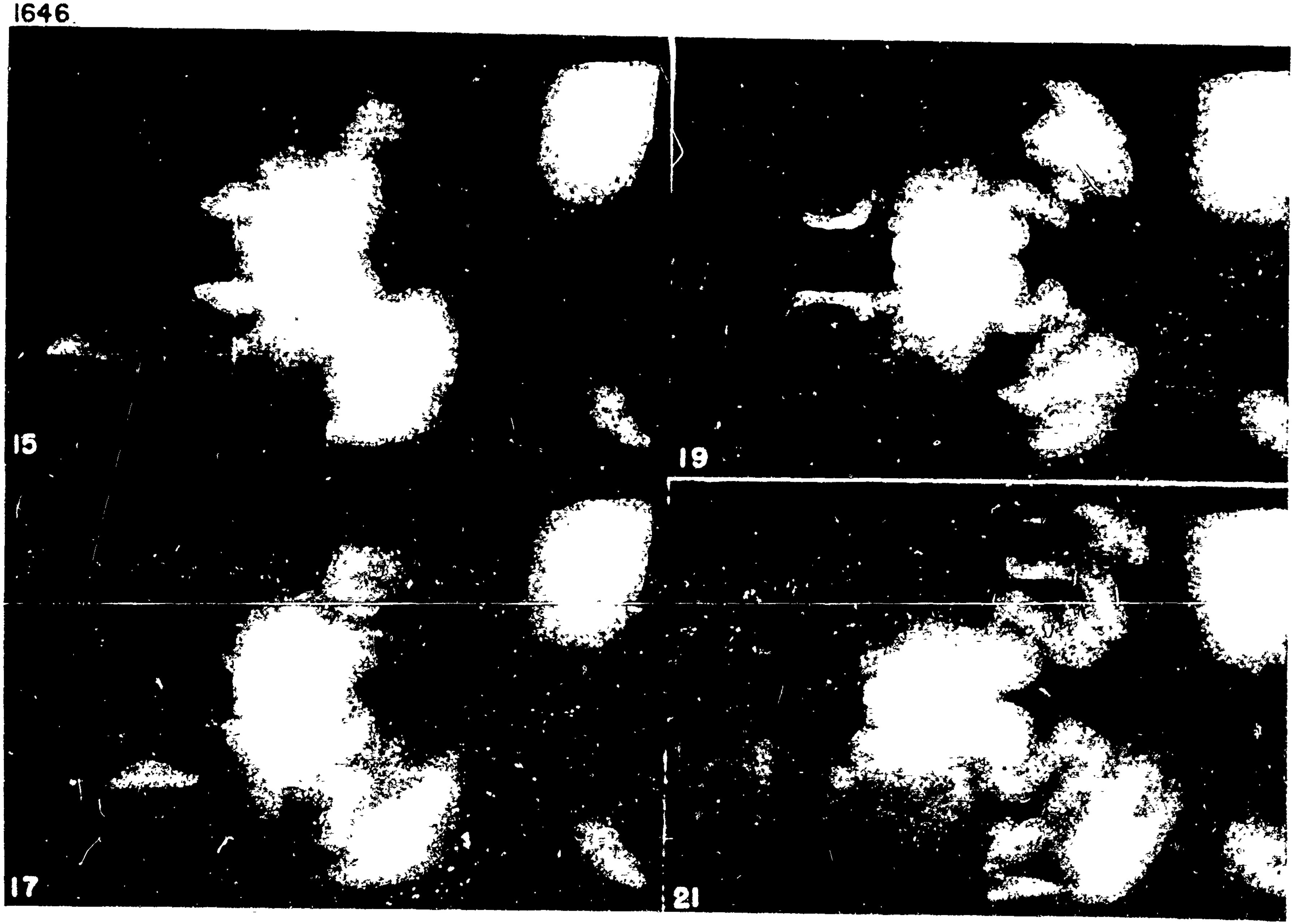

Fig 14 Impact on Lucite block of shock front in air core generated by Tetryl (1646)

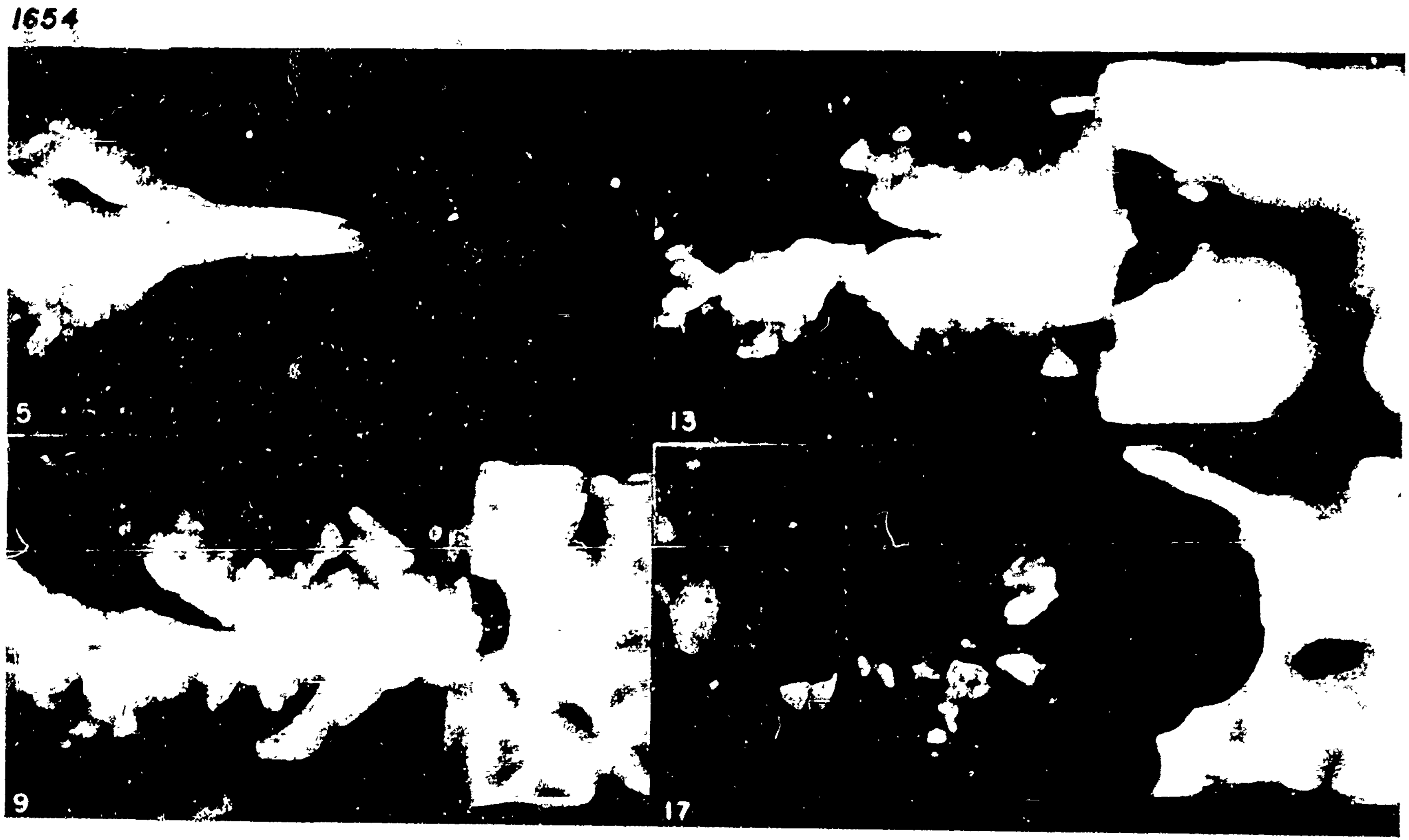

Fig 15 Impact on Lucite block of front in 60/40 (1654)

1655

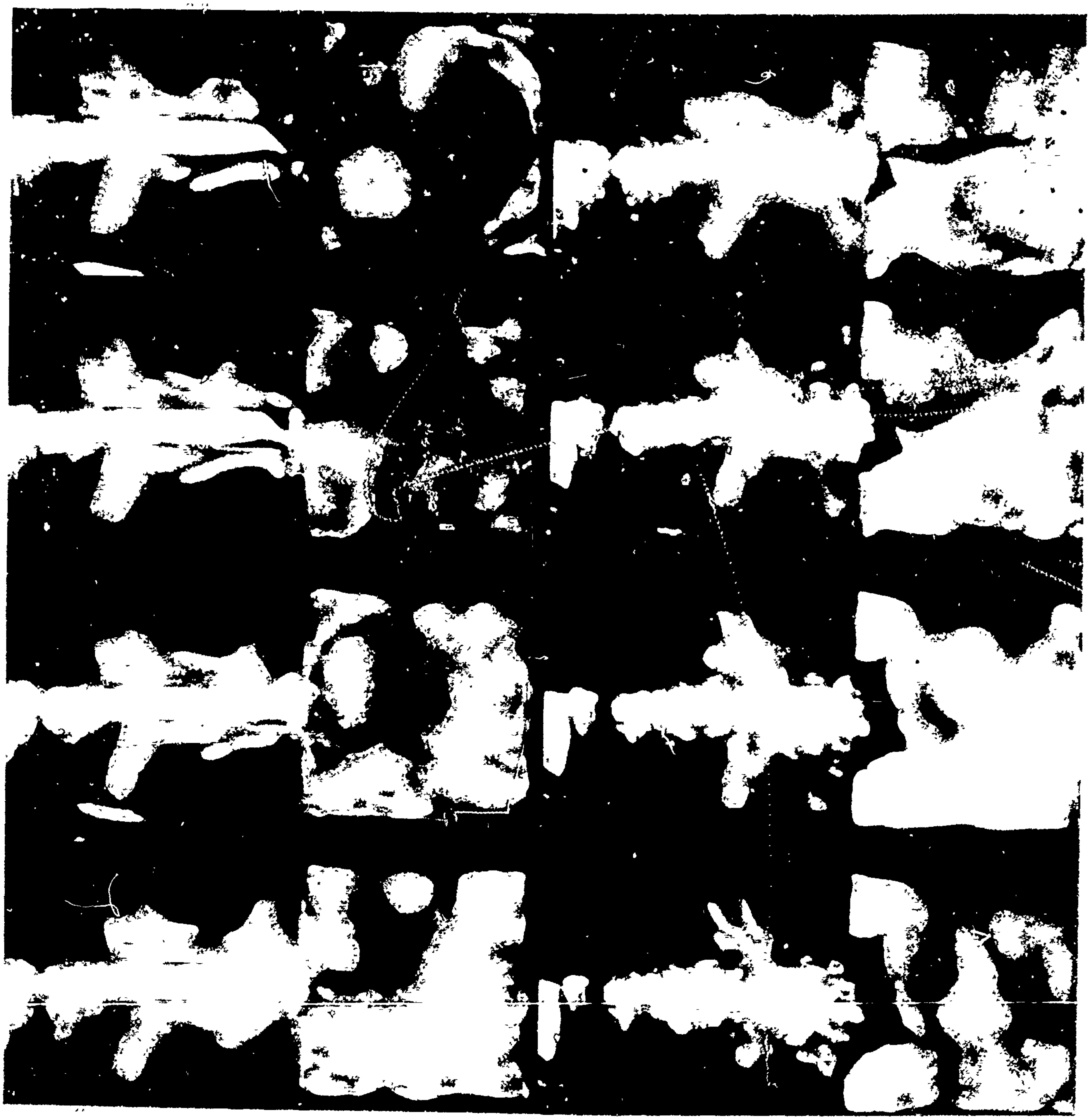

Fig 16 Impact on Lucite block of front in 60/40 (1655)

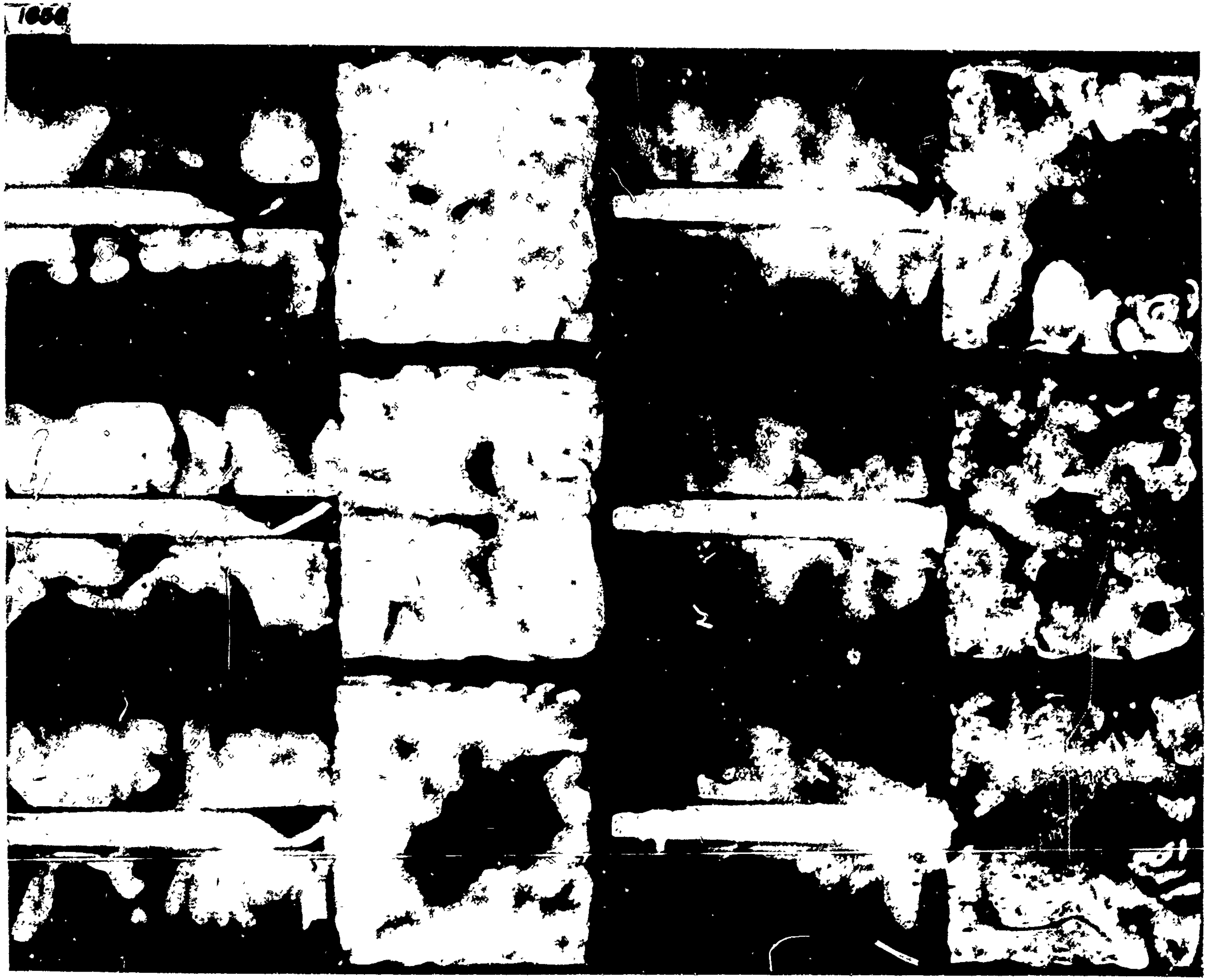

Fig 17 Impact on Lucite block of front in 60/40 (1658)

1653

Fig 18 Lateral fracture propagation in Lucite tube containing 60/40 (1653)

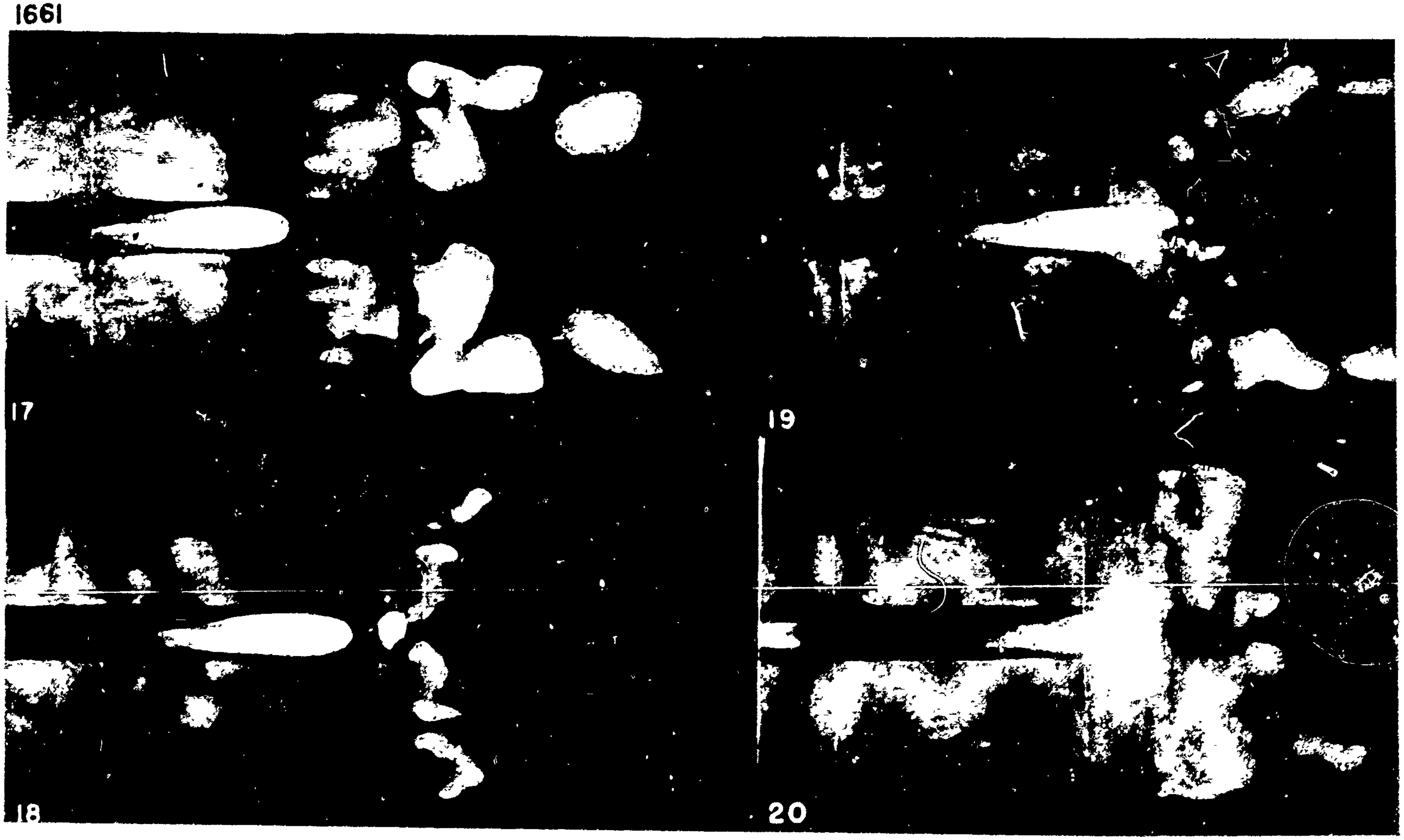

Fig 19 Impact on Lucite block of shock front in air core generated by PETN (1661)

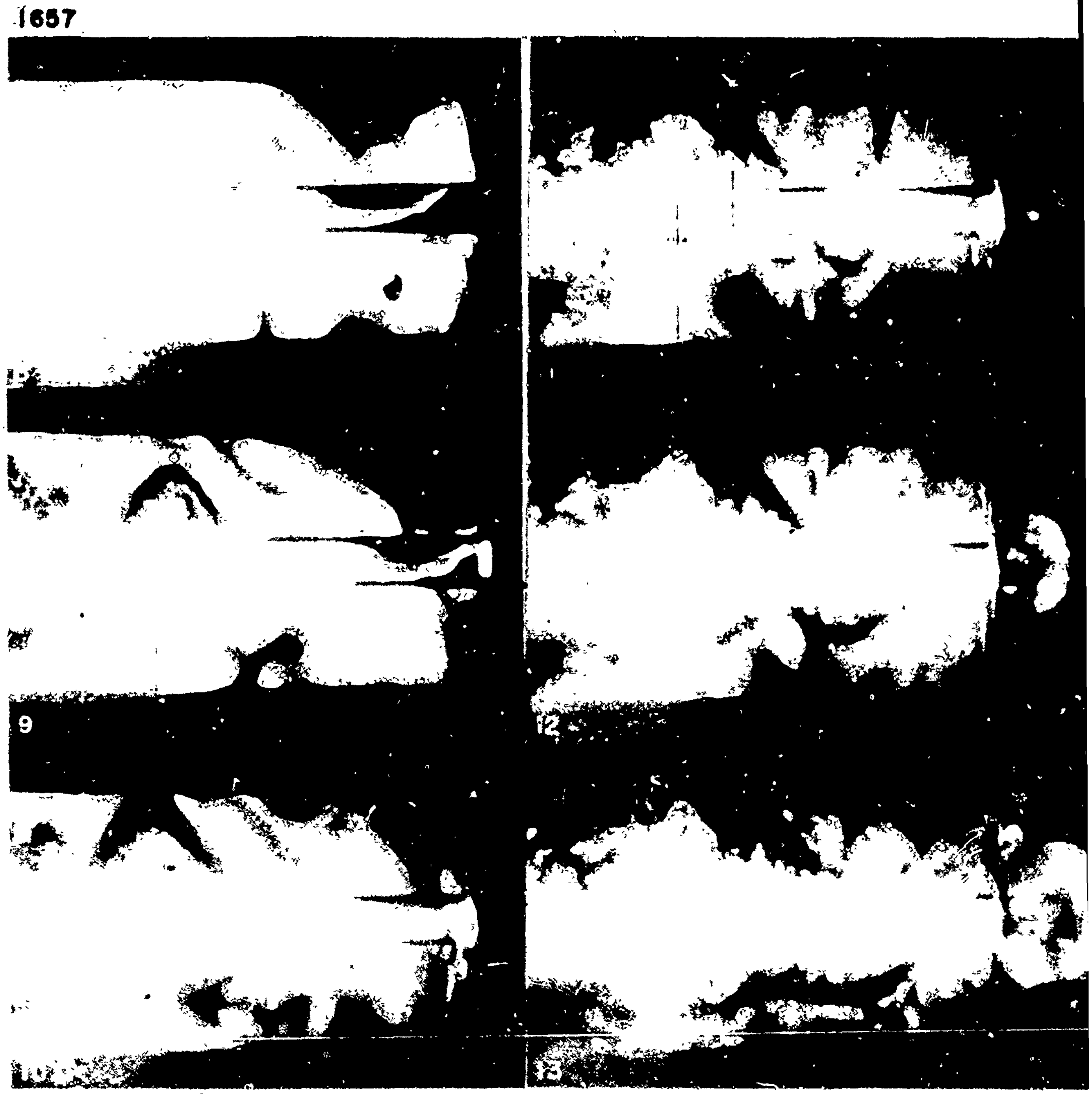

Fig 20 Impact on brass shim of front in 60/40 (1657)

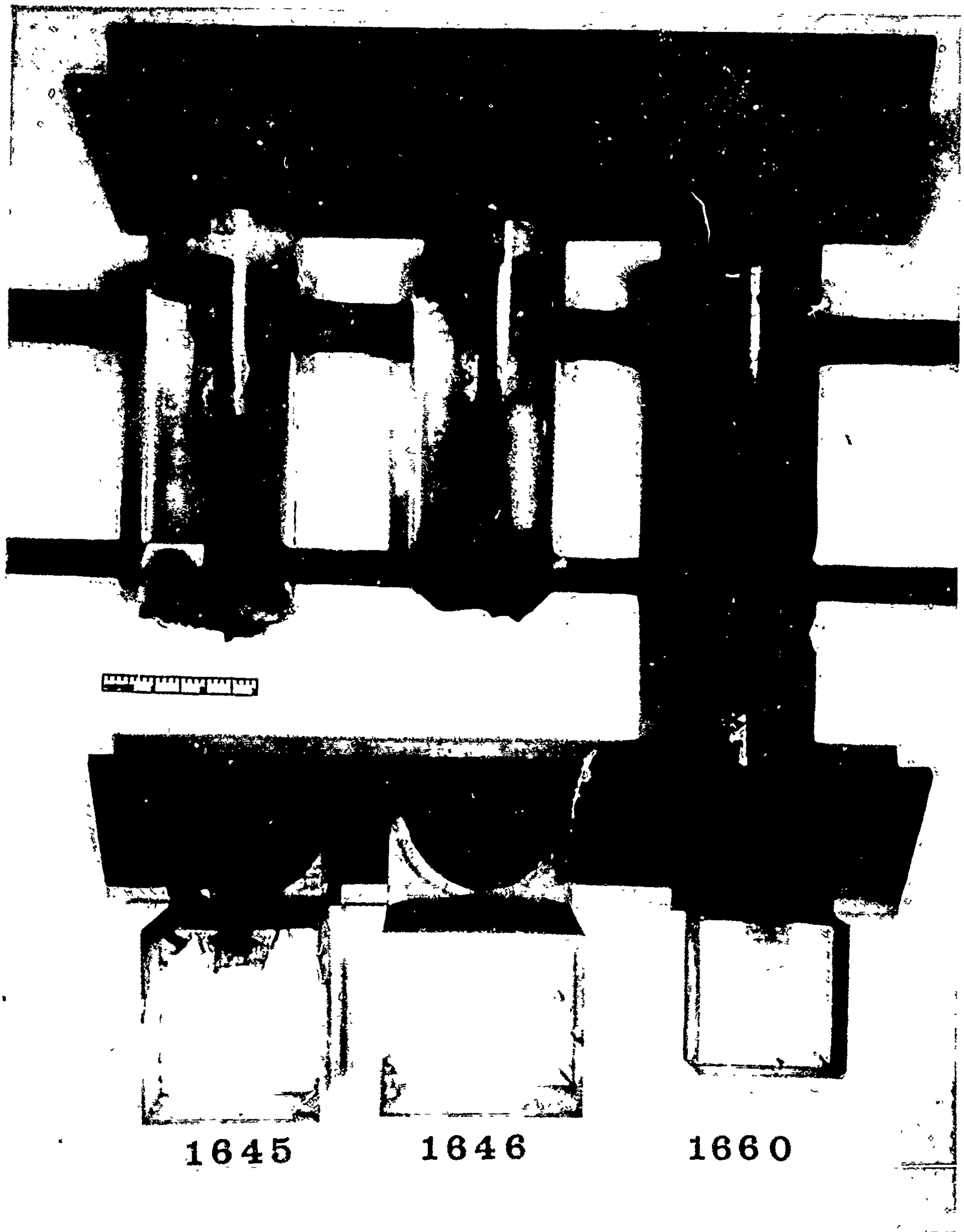

Fig 21 Impact results for air core shocks (supersonic re Lucite) generated by PBX (1645), Tetryl, (1646) and PETN (1660)

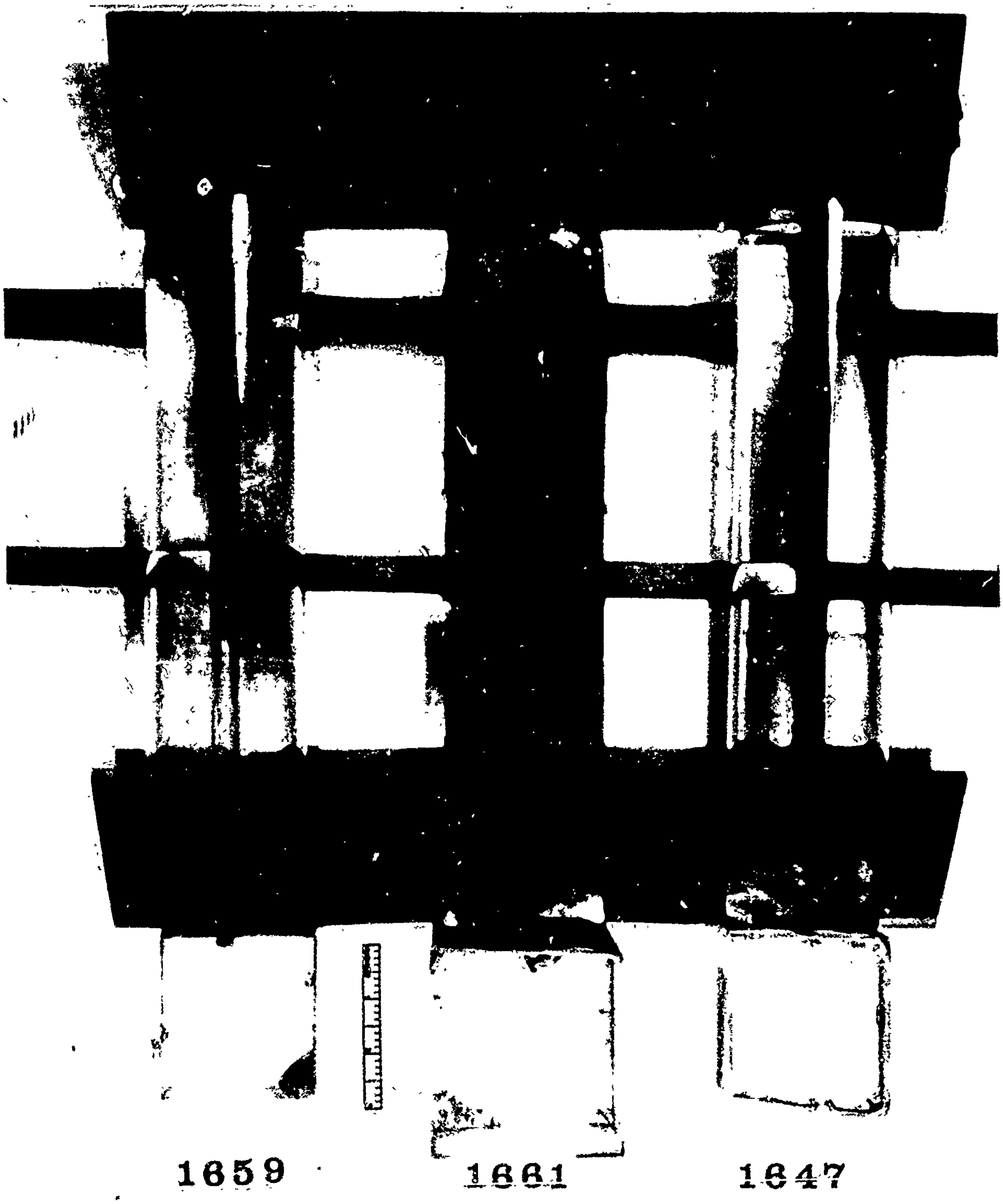

Fig 22 Impact results for reduced strength air core shocks (subsonic re Lucite)(1661, 1647, 1659)

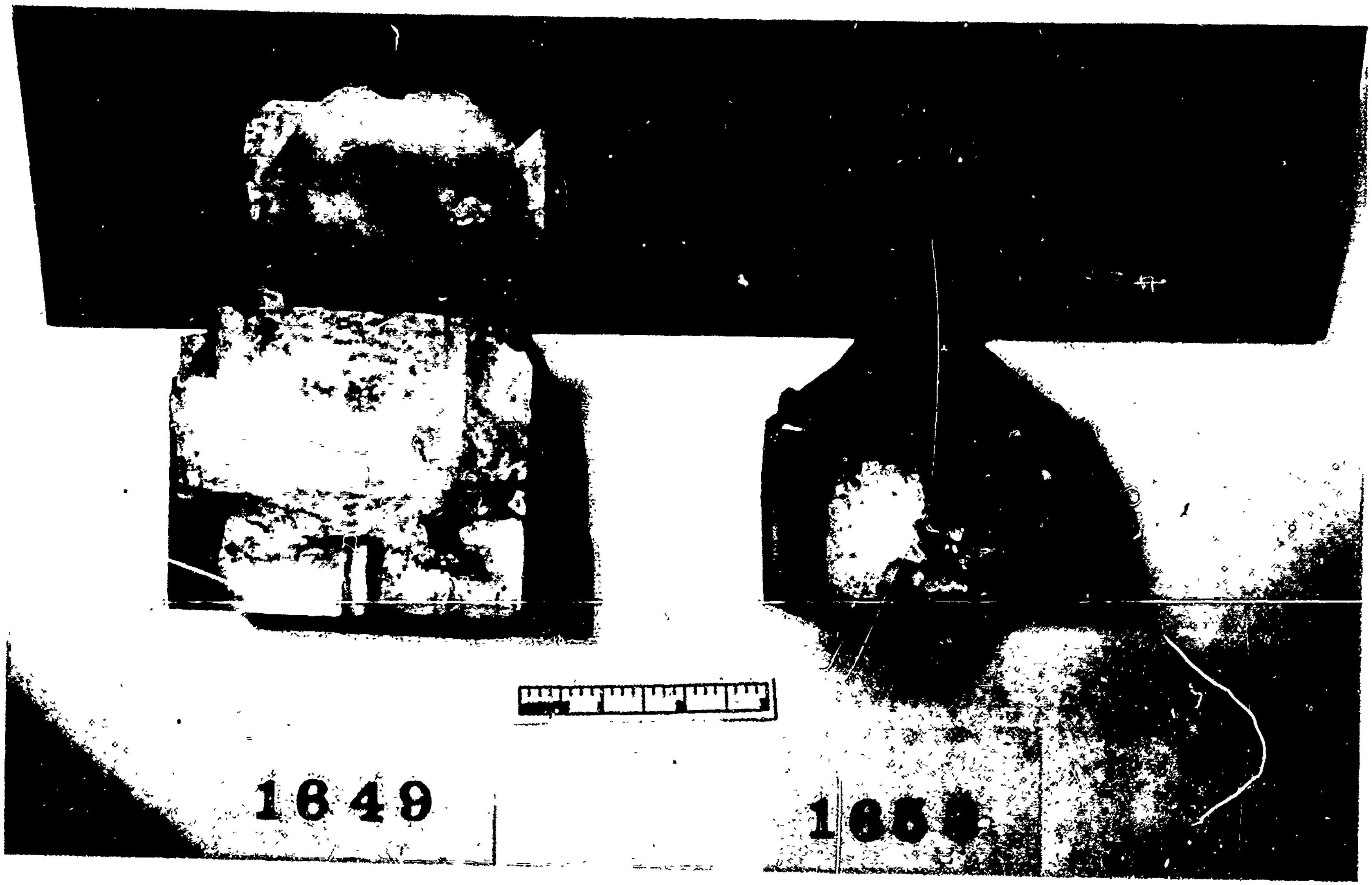

Fig 23 Impact results for an RDX core (1649) and a 60/40 core (1653)